Earthquake Hazards Program ShakeAlert Cooperative Agreement Awards
- Final Technical Report -

Award G19AC00252 (ETH Zurich):

Improving the Performance of the Finite-Fault Rupture Detector (FinDer) Algorithm in the US West Coast ShakeAlert System

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Term covered by this report:
2019/08/15 – 2021/08/14

1. Abstract

This report summarizes the progress made on the **Finite-Fault Rupture Detector (FinDer)** algorithm in the US West Coast ShakeAlert Warning System between **2019/08/15 and 2021/08/14** (award **G19AC00252**). During this time, we (ETH Zurich) continued our close collaboration with our ShakeAlert partners, in particular from Caltech and Univ. Washington, to ensure the highest level of transparency and progress in the project. As proposed, ETH was in charge of all scientific developments and Caltech of all C++ code implementations regarding FinDer. We had regular web meetings (usually 1 per week) and very active email exchanges throughout the two-year period. Unfortunately, we had to cancel both of our planned face-to-face meetings due to the COVID-19 pandemic.

Our work was strongly impacted by the occurrence of the 2019 Ridgecrest earthquake sequence in southern California, including the M7.1 mainshock on July 6. Even though the performance of ShakeAlert was generally considered to be good (Chung *et al.*, 2020), we identified a number of issues in FinDer that needed urgent attention, in particular the handling of latent data. This task was not part of the original proposal, but was strongly encouraged by R&D and ExCom. Nevertheless, we were still able to work through the planned tasks, which led to a significant of improvement of FinDer as described below. The latest version of FinDer passed the ShakeAlert code review and was deployed on eew-ci-int1 in October 2021. We expect the code to be submitted to STP in the next month.

2. Main Body of Report

The following sections briefly summarize the key developments of FinDer during the past 2 years. We (M. Böse, J. Andrews, R. Hartog and C. Felizardo) are currently working on a scientific publication to document the details of this work. We expect this paper to be submitted (possibly to BSSA) by the end of this year.

2.1 Handling of Latent Data

Both FinDer and EPIC underestimated the size of the July 6, 2019, M7.1 Ridgecrest mainshock by 0.8 m.u.. Rapid investigation following the earthquake revealed that in FinDer this underestimation was caused by the strong increase of data latencies at a number of critical near-source stations, combined with an improper handling of these delays in the FinDer waveform processing module, ffd2. The increase of data latencies was mainly due to less efficient data compression and thus increasing sizes of data packets that had to be transmitted to the data center despite limited bandwidth (Stubailo *et al.*, 2020). The ffd2 module discarded wave packets that were older than 5 s, and, as a consequence, peak ground-acceleration (PGA) amplitudes for the affected stations were not any longer updated. The problem was not discovered earlier, because data latencies for the majority of seismic stations along the US West Coast are generally robust and typically << 2 s.

To fix this issue, we moved the latency check from ffd2 to the FinDer core module, which maintains a data window with a maximum configurable age. Additionally, stations that are deemed to have stopped reporting are ignored. The new code ignores amplitudes from trigger stations in the epicentral area if timestamps are older than the theoretically predicted *P*-wave arrival time. Finally, we modified the ffd2 code to ensure that peak values are not overwritten, if wave packets arrive simultaneously or out of sequence. The new FinDer code was approved by ExCom and deployed in March 2020. We documented our findings and solutions in the USGS "*ShakeAlert Performance After-Action Report for the July Ridgecrest Earthquake Sequence*" and in a scientific publication (Chung *et al.*, 2020). Figure 1 compares the performance of the old and new FinDer/ffd2 codes for the M7.1 Ridgecrest mainshock.

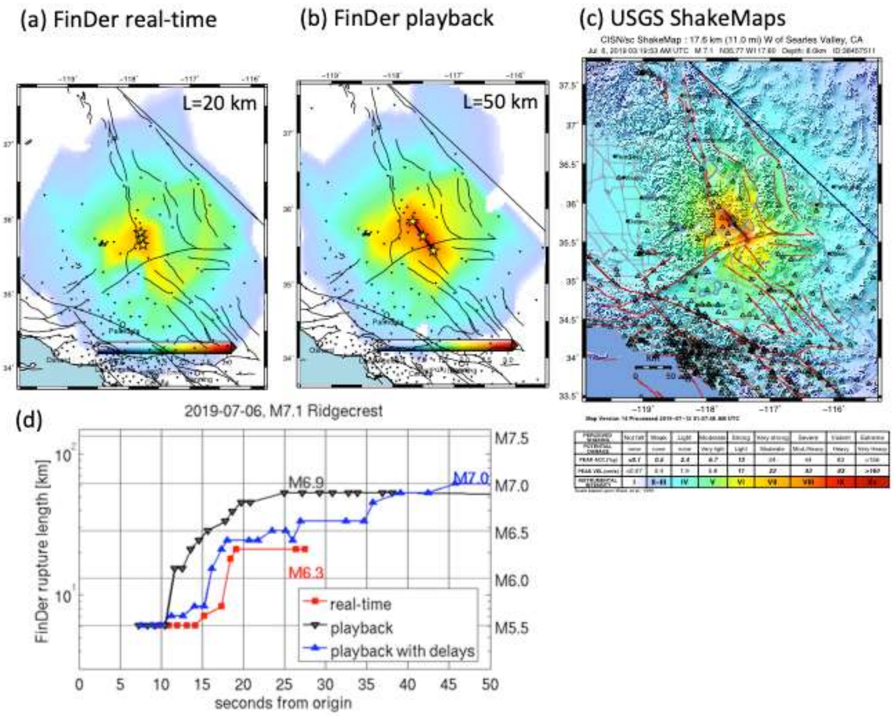

Figure 1. *(a) FinDer underestimated the dimensions of the fault rupture (and thus magnitude) in the M7.1 Ridgecrest mainshock, due to an improper handling of latent data in ffd2. (b) With correct PGA amplitudes passed to FinDer, the final rupture would have been estimated as 50 km long at a strike of 325^o, which is in very good agreement with the finite-fault solution in ShakeMaps (c). (d) The final model is obtained 20-25 s after the event origin, with latencies being neglected, and after 40 s for true (archived) packet delays. The convergence speed, however, can be improved, if a better ground-motion threshold for binary template matching was selected as described section 2.3.*

2.2 FinDer Triggering in Regions with Sparse Instrumentation

Between 03/2018 and 09/2021 FinDer detected and reported 159 M ≥ 4.0 earthquakes in California, Washington, and Oregon. The performance was generally best in areas with dense instrumentation. FinDer's event detection requires (1) a minimum number of stations to exceed a ground motion threshold, and (2) these stations must pass checks for temporal and spatial coherence. In the past, the trigger radius in FinDer was a constant value (in ShakeAlert set to 50 km), which reflects the average station spacing of the seismic network, and thus does not account for varying station densities throughout the region. This can lead to poor/missed event detections in regions with sparse station coverage. We replaced this fixed number by a *dynamic trigger radius* that considers stations actively contributing data to compute a radius at the time of triggering: first we remove noisy and late stations and select stations with PGA values above a configurable threshold; then we check for the spatial coherence of amplitudes reported by these trigger stations.

2.3 FinDer Magnitude Convergence

A fast magnitude convergence is obviously needed in early warning, in particular in large earthquakes. FinDer magnitude is estimated from empirical rupture-length-magnitude relations with the rupture (line-) source estimated from binary template matching for a given ground-motion threshold. We noticed that the convergence speed generally improves, if a larger ground-motion threshold was selected, because larger motions are typically observed in smaller areas and the move-out time is therefore shorter. Limiting the number of ground-motion thresholds for FinDer to search over has the additional benefit of increasing computational speed. We developed a new approach to automatically determine the optimum ground-motion thresholds for FinDer to use in its template matching for a set of observed PGA amplitudes. This is done by minimizing the misfit between the GMPE-predicted and observed areas of shaking for a given threshold. The updated PGA threshold selection favours higher PGA thresholds faster, which results in using data closer to the active fault and therefore higher magnitudes are estimated faster (S-wave available earlier looking closer to fault). This new approach helps achieving a faster magnitude convergence in large earthquakes, for instance, by more than 10 s in the 2016 M7.0 Kumamoto and 2008 M6.9 Miyagi, Japan, earthquakes, and it also helps in the 2019 M7.1 Ridgecrest mainshock, although the main delay in this event is due to late arriving data.

2.4 Handling of Multiple Template Sets

The original FinDer v.1 prototype code supported the usage of multiple template sets: (a) *generic crustal* templates as currently used in ShakeAlert, (b) *subduction-zone* templates and (3) *fault/scenario-specific* templates. This functionality, however, was not implemented when the algorithm was ported to C++. We finally catch up on that important development and implemented a multi-template processing logic. In particular the handling of *fault-specific* templates and the computation of evolving source parameters required some significant code changes. For instance, unlike the generic templates, fault/scenario-specific templates have a fixed geographic location and do not need to be rotated. In order to deal with the additional computational demands, we (Caltech) have implemented multi-threading. This required careful tests and adaptations of the new code, including the monitoring of computational time, CPU and memory usage (Caltech & ETH).

2.5 Fault-Specific Templates for Cascadia and San Andreas

Because of the large azimuthal gap in seismic observations, FinDer tends to map offshore earthquakes too close to the shore. Furthermore, the FinDer line-source approximation falls short in complex ruptures, including those along the Big-Bend section of the San Andreas Fault (SAF). We (ETH) have created templates for a large number (~3'100) of rupture scenarios along the SAF. The Univ. Washington is making good progress in creating templates for scenarios for Cascadia (CSZ). Although our initial results are promising, we expect that the optimization of this important new component of FinDer will need to be continued for the next couple of months, before the fault-specific template processing can be turned on. It is important to point out that these new templates are not intended to replace the current generic templates, but they will improve FinDer's performance in future great earthquakes along the CSZ and SAF. With the handling of multiple template sets implemented, adding more template sets (for other faults) in the future is straight-forward.

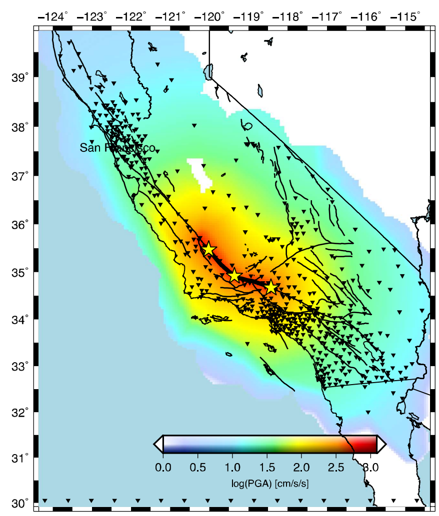

Figure 2. *Testing of the new multi-threaded multi-template code: FinDer finite-source solution for a scenario earthquake along the San Andreas Fault.*

2.6 FinDer/ShakeAlert in Complex Earthquake Sequences

The Complex Sequences Working Group (Chair: M. Böse, ETH; Members: J. Andrews, D. Kilb, A. Chung, C. O'Rourke) has been charged to develop synthetic event data sets to test the behavior of ShakeAlert during complex earthquake sequences. A correct event separation in such extreme sequences is challenging, because the waveforms from temporally neighbored events will begin to overlap at a certain time into the events. That is, the observed ground-motions cannot be easily assigned to a specific event anymore. While the work in our group is still on-going, we identified a number of problematic scenarios (Böse *et al.*, 2021d). For FinDer we found that when multiple earthquakes occur close in time (~2-3 minutes) and the events are in the same source region (e.g. foreshock-mainshock or mainshock-aftershock pairs) FinDer will merge these events into a single detection, i.e. assign the same eventID. For events in different source regions, FinDer will start processing the first event and switch later to the event creating the strongest ground-motions, which is either in the same or in another source region. Again, FinDer will not update the eventID, implying that the FinDer point-source parameters in this scenario refer to the first and its line-source parameters to the largest event (see “Technical Report of the Complex Sequences Working Group”, section 3 of this report).

The ultimate goal of FinDer is to provide a description of spatially distributed ground-motions, which with the current processing logic is achieved (Figure 3). The main problem, however, is that the correct association with output parameters from another algorithm, such as EPIC, will likely fail. Associating estimates from multiple algorithms in the ground-motion rather than source-parameter space will probably obviate this problem in the future. The Complex Sequences Working Group and FinDer Group will continue this study in the current research phase and make recommendations on configuration and code changes as needed. Note that FinDer multi-event processing is not fully implemented.

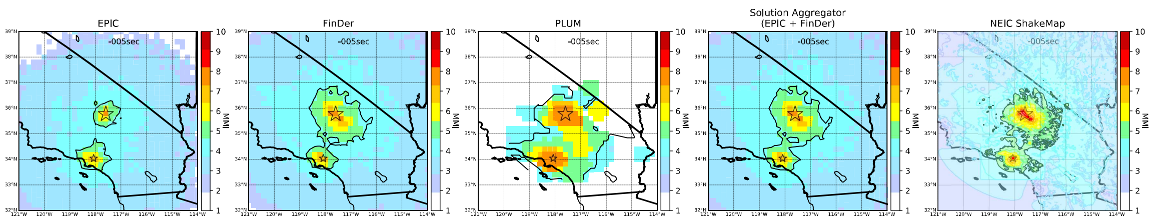

Figure 3. *Predicted (columns 1 to 4 – EPIC, FinDer, PLUM & SA) and observed (column 5) MMI distribution for a M6.0 earthquake in Los Angeles followed 5s later by a M7.1 in the Ridgecrest area. Black lines show the MMI4.5 contour. The scenario is obtained by scaling and summation of waveforms observed during the 2020 El Monte and 2019 Ridgecrest earthquakes (‘composite waveforms’).*

2.7 Others

How often can EEW Systems Alert Sites with High-Intensity Ground Motion?

Together with our ShakeAlert partners we tested EPIC, FinDer and PLUM for large crustal and subduction-zone earthquakes in Japan (Meier *et al.*, 2020). We found that 40% to 60% of sites with strong to extreme ground motions could theoretically get alerts with warning times of more than 5 s. In a second (not USGS-funded) follow-up study, we extended this kind of analysis to earthquake loss (Böse *et al.*, 2021c).

Magnitude Saturation in Large Earthquakes

We actively contributed to a short-term Working Group to address the problem of magnitude saturation in large earthquakes. EPIC determines magnitudes from peak displacement using a time window of up-to-four seconds. This implies that EPIC magnitude estimates will saturate in large events (as seen in the M7.1 Ridgecrest earthquake). FinDer magnitude estimates, on the other hand, should not saturate because they are determined from spatially distributed ground-motion patterns rather than absolute amplitudes. The Working group recommended that for small earthquakes (M < 6.0) the EPIC solution should be weighted approximately 5 times more than the FinDer solution. For large earthquakes (M ≥ 6.0), the FinDer solution, however, shall be preferred, provided that it exceeds the EPIC estimate. The new SA rule was approved by ExCom and deployed in June 2020.

Quantification of Uncertainties

We continued our work with regards to a better quantification of uncertainties of the FinDer models. In Böse *et al.* (2021a) we established empirical relationships between the azimuthal gap between observed amplitudes and FinDer errors in the length and orientation of the line-source models. In Li *et al.* (2021) we investigated the relationship between station density and FinDer triggering.

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3. Project Data

All FinDer/ffd2 code updates and fault-specific templates for the SAF have been checked into the ShakeAlert repository (in Caltech's responsibility). The Complex Sequences Working Group (chaired by ETH) will hand-over all earthquake synthetics used for their testing to STP (a copy is already available on the ShakeAlert dev machines). The progress in this group is documented in
https://docs.google.com/document/d/1qPBY7hipRBcjnd8h26JpEKv6VR2rgCg-vEDtffUEtss/edit
(work in progress) on the ShakeAlert google drive.

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